STATIC AND MODAL ANALYSIS OF UNIFORM AND CONFORMAL LATTICE STRUCTURE IN SPUR GEARS FOR LIGHTWEIGHT ADDITIVE MANUFACTURING DESIGN

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ABSTRACT

Additive manufacturing enables the design and manufacturing of complex forms for metal end-user parts. This contributes to weight reduction and performance improvements by integrating lightweight, high-strength structures such as lattice structures in part design enhancements. Lattice structures have many configurations, based on the type, arrangement and density of unit cells. However, the optimum configuration design for lattice structures is yet to be fully understood. Therefore, the objective of this study is to compare the mechanical characteristics of conformal and uniform lattice structures. Two spur gears are designed with conformal and uniform lattice structures. Static and modal analyses were performed, and the results were compared. The results show that conformal lattice structures with a strut diameter of 4 mm have better performance than uniform lattice structures. The results obtained demonstrated that conformal lattice structures have the highest natural frequency with 405.17 Hz for the first mode, the second is the uniform lattice structure, and the lowest in the solid spur gear. This shows that lattice structures can improve spur gear performances and reduce vibration. In conclusion, the uniformity of the lattice structure influences the behaviour of the part, and conformal lattice structures have better mechanical characteristics than uniform lattice structures. The contribution from this study can be applied in the design of spur gears for the automotive industry to increase performance and weight reduction, in return reduce fuel consumption and carbon emissions for a greener environment.

***Keywords**: Additive manufacturing, spur gear, lattice structures, finite-element analysis*

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1.0 INTRODUCTION

In the last decade, additive manufacturing has evolved from a prototyping process in the 1990s to a manufacturing process [1]. It is now possible to manufacture not only prototypes but also end-user parts which meet part requirements and can be applied in the automotive, biomedical and aerospace industries [2,3]. Additive manufacturing enables the manufacturing of complex forms which were previously difficult to manufacture using conventional manufacturing processes. It is now possible to manufacture complex forms such as lattice structures without significant added cost [4].

Lattice structures are an example of architectured material, where the principle is to add material only where is required. Lattice structures can be previously manufactured using other manufacturing processes, such as die-casting and wire-cutting [5,6]. However, it is a difficult and complex process and high-cost and limited to certain lattice structure types only [7]. However, additive manufacturing can now easily manufacture any lattice structure type with different densities and shapes. Hence the increased interest in lattice structure integration in part designs.

The advantages of integrating lattice structures in part designs are weight reduction [8,9], increased performance and functionality [10,11], and heat dissipation [12-14]. There are many lattice structure configurations, such as types, density, and uniformity. Uniform lattice structures are designed independently of the outer part's surface, with conformal lattice structures following the curvature of the outer lattice structure form [15]. However, the impact on mechanical properties and influence on the design of conformal and uniform lattice structures are yet to be fully understood. Figure 1 shows an example of Ti-6Al-4V cubic uniform lattice structures manufactured using Selective Laser Melting (SLM) machine.

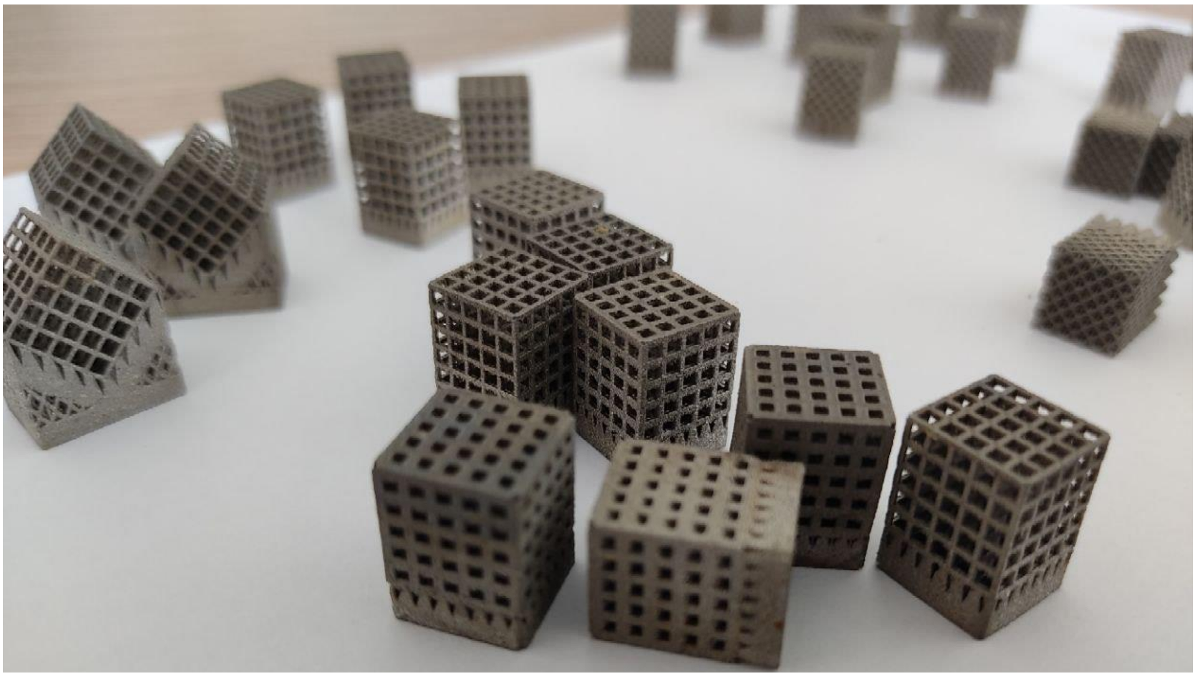

Figure 1: Lattice structures manufactured using additive manufacturing Selective Laser Melting (SLM) machine

There is a significant potential for integrating lattice structures in spur gears for weight reduction and performance improvements [16]. The current manufacturing process of spur gears includes casting, rolling, forging and cutting. However, unlike additive manufacturing, these processes are limited to manufacturing full solid spur gears and are unable to manufacture complex hollow and porous spur gears with lattice structures [14]. Solid spur gears are heavy gears and contribute to the source of vibration [17]. Most spur gears have stress values far from the designed stress limit. Spur gears are commonly manufactured using cast iron. A recent study demonstrated design improvements using carbon fibre to reduce stress and strain. However, it is still based on full solid designs, which contribute to a higher natural frequency. The integration of lattice structures in spur gears has the potential to increase its natural frequency and reduce vibration in spur gears [18]. The design and mechanical properties of lattice structures are yet to be fully understood and widely applied in the automotive and aerospace industries [19-20]. Lightweight additive manufacturing parts have been designed and optimised in the aerospace industry. Design improvements to bracket designs based on topology optimisation and lattice structures have reduced the mass of parts and in return increases fuel efficiency [21]. There is a big potential for designers and researchers to change the design of spur gears to reduce mass, reduce vibration and be able to withstand the load that will be carried. Therefore, this research aims to compare and analyse the mechanical characteristics between uniform and conformal lattice structures in spur gears.

2.0 METHODOLOGY

Figure 2 shows the flowchart of the methodology conducted in this research. First, the lattice structure parameters and configurations were identified. In the second step, uniform and conformal lattice structures were created from the configurations identified. Next, static and modal analysis finite-element analysis (FEA) were performed, and finally, the results were compared to determine the differences in the mechanical characteristics between uniform and conformal lattice structures integrated into a spur gear. In this research, the lattice structure parameters identified are lattice structure patterns, diameter, uniform, or conformal, as shown in Figure 3.

The values for the spur gear are listed in Table 1. All the spur gears consist of 23 teeth with a 10 mm width and 95 steepness diameter. First, the design space and non-design space must be identified. The design space is the volume in the part where the lattice structure can be integrated and designed, while the non-design space is the volume where the design is maintained, as shown in Figure 4. The non-design space depends on the functional surface of the part for assembly and force application. The CAD uniform and conformal lattice structure models are created in Figure 5.

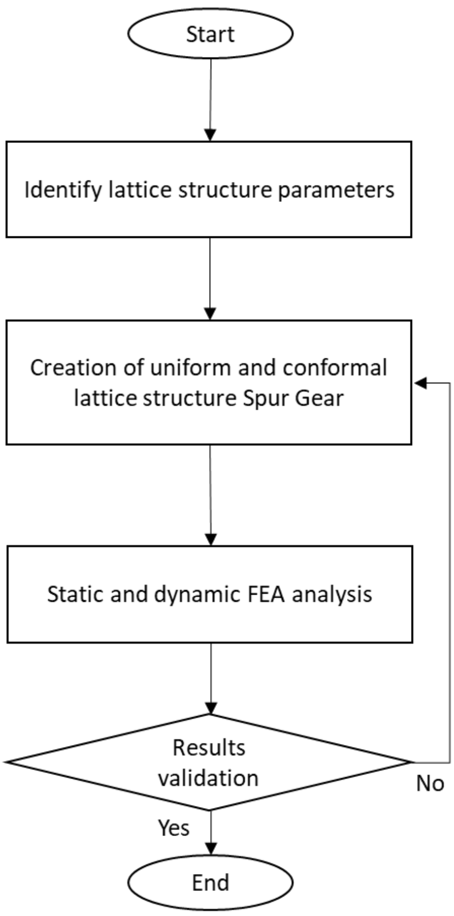

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Figure 2: Flowchart of the methodology

Table 1: Configurations for the spur gear

Configurations	Value
Number of teeth	23
Modules (mm)	2.5
Angle of stress (°)	20°
Width (mm)	10
Steepness diameter (mm)	85
Basic diameter (mm)	79.874
Root diameter (mm)	78.558
End diameter (mm)	90

The lattice structure parameters consist of the type of lattice structure, the diameters, and conformal or uniform lattice structures. In this study, the type chosen is the cubic lattice structure. The diameters chosen for the struts of the lattice structures in the spur gears are 2 mm, 3 mm and 4 mm. Additive manufacturing constraints must be considered in the design of the lattice structures in the spur gears. For parts to be manufactured using Selective Laser Melting (SLM) machines, the truss must have a minimum 0.2 mm diameter, with a maximum length of 10.0 mm without requiring a support structure. The draft angle must be between 45 to 90°.

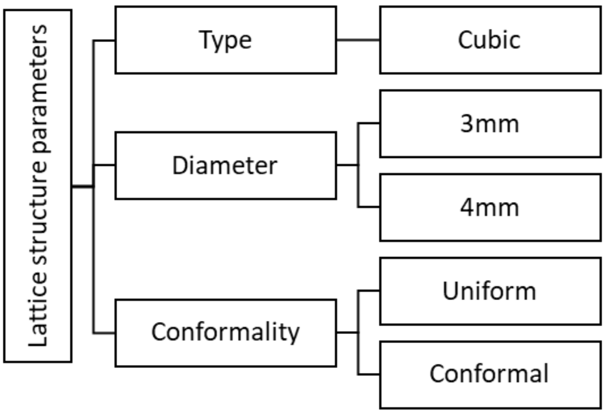


Figure 3: Lattice structure parameters

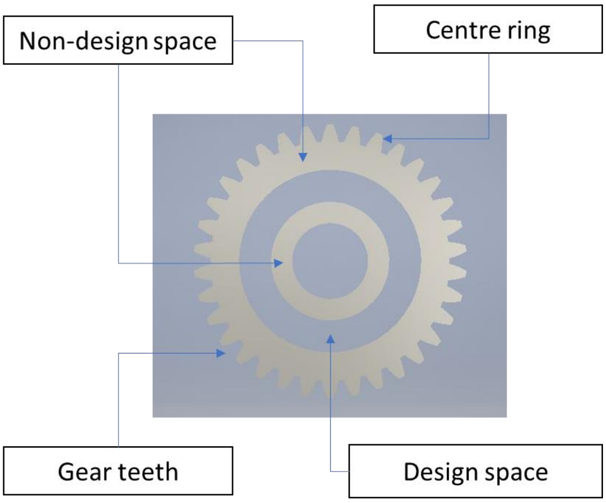
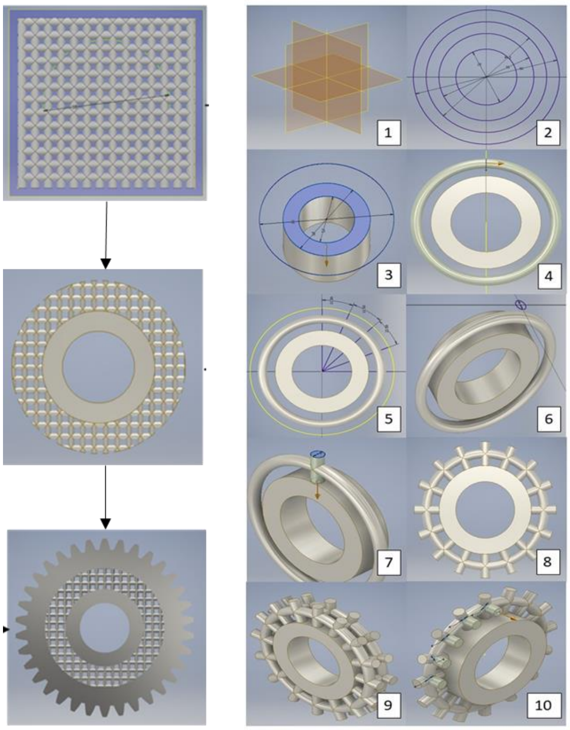


Figure 4: Design space and non-design space in the spur gear

Conformal cubic and uniform cubic lattice structures were selected for this research study. The lattice structure patterns can be uniformly classified as periodic lattice structures. The two patterns have different configurations, as shown in Figure 6.



(a) (b)

Figure 5: Creation of (a) uniform lattice structures and (b) conformal lattice structures in the design space

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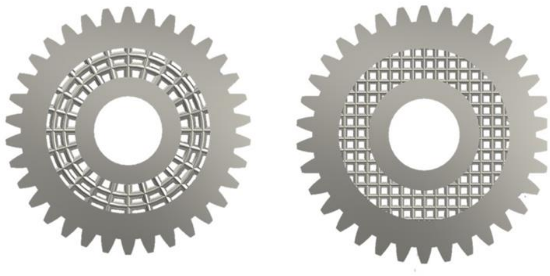

(a) (b)

Figure 6: (a) Conformal and (b) uniform lattice structures

Analysis using the finite element method is essential to ensure that the design of the lattice structure is optimized correctly according to the set criteria. Static, and modal analysis was conducted in this research to investigate the spur gear in static and rotating conditions. The simulation was implemented to determine and compare the mechanical behaviour of uniform and conformal lattice structures. The boundary conditions and suitable meshing sizes were determined and applied in the simulation. The boundary conditions and size of the mesh depend on the geometry of the part and the force applied to the part. The torque applied on the gear in 100 Nm. After the spur gear design was completed, the mass and weight reduction between the lattice structure spur gears and solid spur gears were calculated. The load applied to the spur gear is applied on the sides of each gear tooth, as shown in Figure 7. It is considered that the gear tooth collided with the connecting gear's tooth or pinion. A non-friction condition is applied to the inner surface of the centre coil to ignore the value of friction that results when the gear rotates.

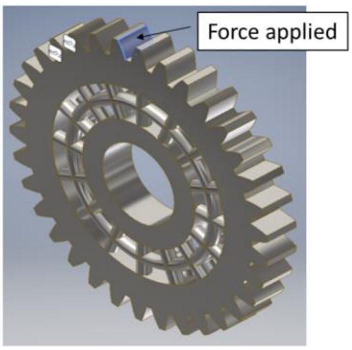

Figure 7: Force applied on the spur gear

Static simulations were performed using Autodesk Inventor. The simulation was conducted to determine the maximum value of von Mises stress and the safety factor for each gear. The values are then compared to the values with the maximum stress value of the solid spur gear. From the data, the characteristics of each gear produced can be identified. The input for the simulation is the selected material, the total load and the boundary conditions. Boundary

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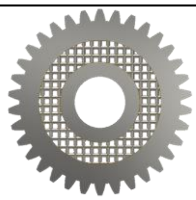
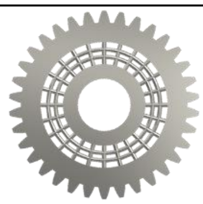
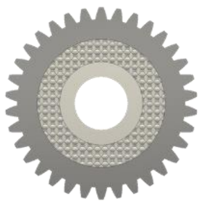
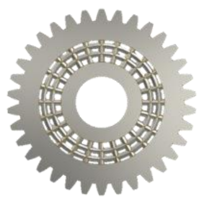
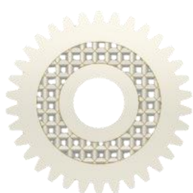
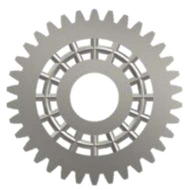
conditions play an important role in FEA simulations. Negligence in the selection of incorrect boundary conditions will affect the final results of the simulations performed. The boundary conditions are also the same for each gear simulated. The material used in this project is Ti-6Al-4V. A moment is applied to the centre coil, which is considered a rotation from the shaft to the gear. The moment value is the same for all the resulting gears.

Modal analysis was also performed in this research as the spur gear is mainly in rotation in its working condition. The purpose of performing this simulation is to determine the value of the resulting natural frequency on all gears. Then, all the data obtained are compared with the natural frequency value for solid spur gear. There are 8 pre-set modes. As in static simulations, dynamically performed simulations also require the selection of precise boundary conditions. In this case, a set condition is placed on the surface area of one of the gear teeth as shown in Figure 7.

3.0 RESULTS AND DISCUSSION

Two patterns of lattice structures were created and the resulting differences between the two were compared. In this research, conformal cubic lattice structure spur gears were designed using three different diameters; 2 mm, 3 mm and 4 mm. The same parameters are chosen for the uniform cubic lattice structure spur gears. All the uniform and conformal lattice structures are shown in Table 2.

Table 2: Uniform and conformal lattice structures based on each parameter

Diameter (mm)	Uniform lattice structure	Conformal lattice structure
2		
3		
4		

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3.1 Static analysis

In this section, the results from the static simulation are presented for the solid, uniform, and conformal lattice structures. From the von Mises results, the performance of the spur gear can be evaluated.

3.11 Solid spur gear

The first simulation was performed on a standard solid spur gear as a reference point for the comparison of uniform and conformal lattice structures. The resulting von Mises stresses were recorded, and the distribution of the resulting stresses was also observed. From the stress distribution, the areas that are suitable to be optimised can be observed, which are the design space. Therefore, it can be improved and the solid material is suitable to be replaced with lattice structures.

From the results for the solid spur gear, it is observed that many areas have minimal stress and strain when the load is applied. But in some areas, the area is exposed to stresses very close to the allowable stress limit. This causes unoptimized designs which do not make full use of the designed domain area. Solid spur gears' mass is higher compared to the lattice structure spur gear. The spur gear has a mass of 0.232 kg and the results obtained for the von Mises stress is 197.8 MPa. The results obtained for the solid spur gear are shown in Table 3 and Figure 8.

Table 3: Results obtained for solid spur gear

	Value
Von Mises stress (MPa)	197.8
Diplacement (mm)	0.01144
Mass (kg)	0.232
Safety factor	1.3

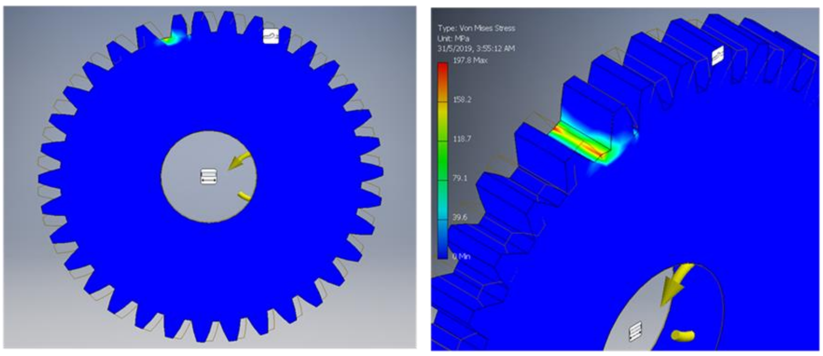

Figure 8: von Mises stress obtained for the solid spur gear

3.12 Uniform cubic spur gear

To optimize the spur gear, uniform cubic lattice structures were designed. The steps to create the CAD models of the uniform cubic spur gears have been discussed in the methodology. The struts are designed to be round in shape, and three different types of strut diameters have been produced as variables in this study. Table 4 shows the results obtained after performing the finite element method on a uniform cubic patterned spur gear for each diameter.

Table 4: Results obtained for uniform lattice structure spur gear for each diameter strut thickness

Diameter	2 mm	3 mm	4 mm
Von Mises stress (MPa)	285.7	302.2	244.4
Diplacement (mm)	0.017	0.013	0.014
Mass (kg)	0.192	0.221	0.204
Safety factor	0.98	0.91	1.13

Based on the results obtained, two and three millimeters are unsuitable diameters for spur gears that use a uniform cubic lattice structure. This is because the resulting safety factor is less than one. The safety factors of the spur gear are 0.98 and 0.91. For lattice structures using a diameter of four millimetres, the safety factor exceeds one, so the diameter is considered safe and acceptable. The spur gear with a diameter of four millimetres obtains the smallest maximum stress. However, solid spur gears' maximum Von Mises stress is smaller than that of all uniform cubic-patterned spur gears. This is because the spur gear's lattice structure is not optimized as a whole. Each vertex on the lattice structure should be optimized using the fillet option. In this way, the concentration stress can be reduced, thus reducing the maximum von Mises stress on the spur gear.

3.13 Conformal lattice structures

Conformal cubic patterns can be categorized as irregular patterns. Conformal means the lattice structure is designed to follow the product's shape. To perform the optimization of the spur gear, a conformal cubic patterned lattice structure was used. The production method of conformal cubic spur gears has been discussed in the previous section. Because the struts are designed to be round in shape, three different types of strut diameters have been produced as variables in this study.

Based on the results of the study obtained, all spur gears using conformal lattice structure patterns have a safety factor higher than one, as shown in Table 5. Therefore, all three forms of gear are considered safe and can be taken into account in selecting the ideal shape. Conformal spur gears using 4 mm diameter have the smallest stress among other conformal spur gears. This is because the larger the diameter of the strut, the less stress is acting on it. The conformal design is also suitable for transferring force acting on the spur gear. Figure 9 shows the mass reduction and comparison for each spur gear.

Table 5: Results obtained for conformal lattice structure spur gear for each diameter strut thickness

Diameter	2 mm	3 mm	4 mm
Von Mises stress (MPa)	266.1	263.3	228.2
Diplacement (mm)	0.020	0.014	0.016
Mass (kg)	0.181	0.203	0.191
Safety factor	1.04	1.05	1.21

Based on Figure 9, the solid spur gear has the highest mass. In contrast, gears that use conformal cubic for 2 mm diameter have the lowest mass. According to Figure 9, the conformal cubic is better than uniform cubic lattice structures. Spur gears with conformal cubic lattice structures are found to have a lighter weight than uniform cubic. The conformal design follows the designed outer curvature of spur gear. Thus, the orientation of the moving load is optimised to perform the stress transfer. Therefore, conformal cubic lattice structures do not require many structural layers or large diameters to accommodate the load on the gear teeth. Thus, the mass of conformal lattice structure spur gear can be reduced.

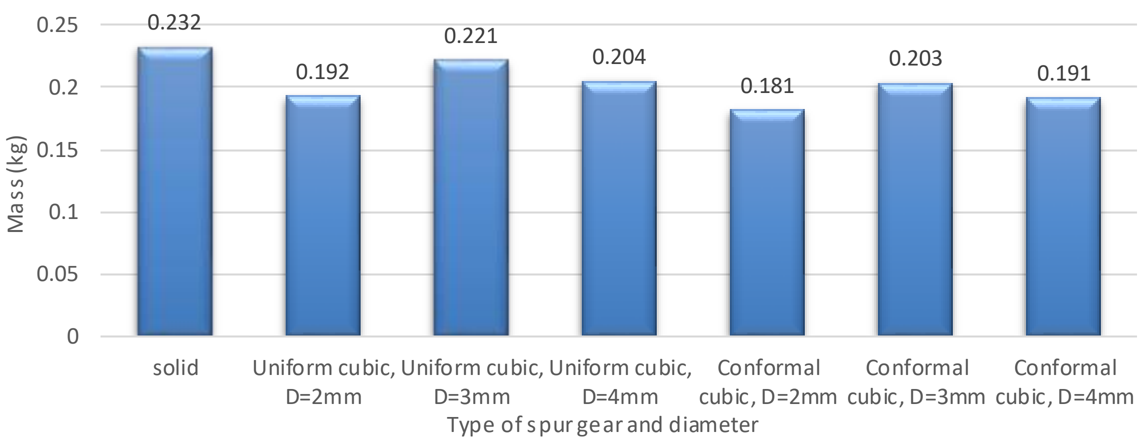

Figure 9: Mass for each spur gear

Figure 10 shows the von Mises stress for each spur gear and diameter with safety factors of more than one. Spur gears using a uniform cubic pattern and additional gears for 2 mm and 3 mm diameters are not placed in Figure 10 as they do not meet the parts requirements. Based on Figure 10, the solid spur gear stress is the lowest stress among all types of gears that have been produced, which is 198 MPa, followed by the second lowest, which is the conformal cubic spur gear with a diameter of 4 mm. From these situations, it has been proven that although solid spur gears have the lowest stress, the conformal cubic patterned lattice structure is the

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ideal design among all gears designed because it is lightweight with a mass of 0.191 kg and has the lowest stress among other gears produced.

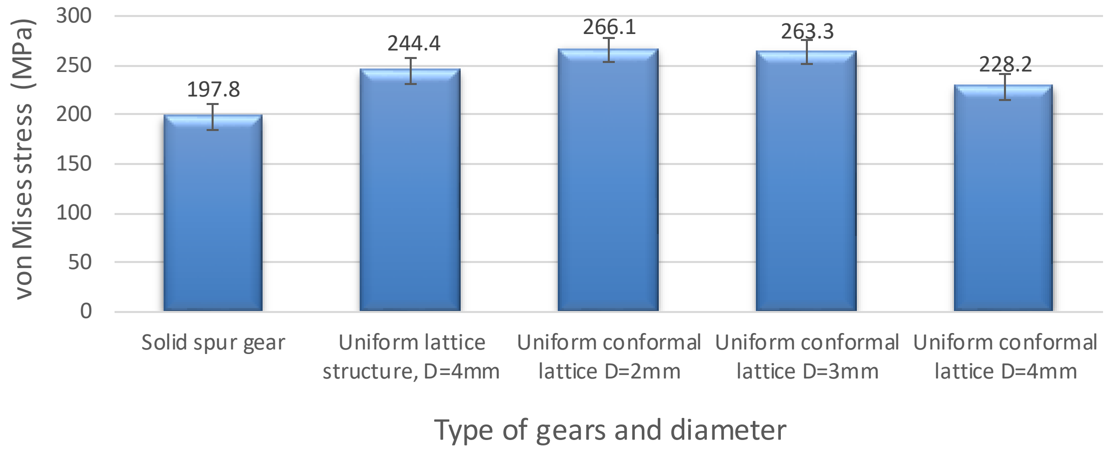

Figure 10: von Mises stress obtained for each spur gear

3.2 Modal analysis

Modal analysis was performed to determine the natural frequency produced on the spur gear. Eigenvalue analysis was performed and determined. According to Xiao et al. [21], the vibration on the gear is transferred starting with the tooth surface, gear body and lattice structure, axle, bearing, pedal bearing, and gearbox. The modes applied to each spur gear are eight. For modal analysis, only spur gears with dimensions of 4 mm were used to differentiate their results from solid spur gears. According to the results of the study from the static simulation, the data show that the spur gears using a diameter of 4 mm have the best performance compared to the spur gears having a diameter of 2 and 3mm.

Figure 11 shows the position of each mode produced in two-dimensional form. The round shape is considered a spur gear or a cross-section of a spur gear. The fixed state is placed on one of the gear tooth surfaces. The higher the mode, the more vibrations are produced. The mode closest to the fixed state does not have much vibration or no vibration at all. The farthest mode area with a fixed state, or in this case, mode eight (mode 8), will produce the strongest vibration due to the load transfer involved. For reference, the nodes and elements on the gear are set by default. The selected nodes are 10334, and the resulting elements are 6148. The resulting natural frequency values at each mode can be referenced in Table 10.

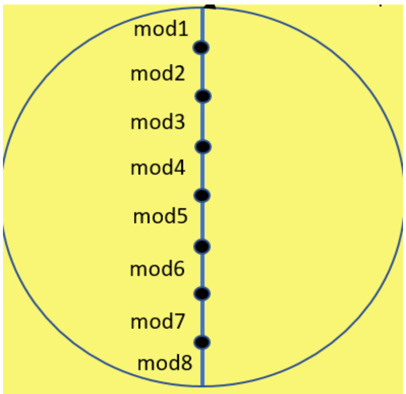

Figure 11: Positions of each mode in 2 dimension

Table 10: Natural frequency of the solid spur gear

Mode	1	2	3	4	5	6	7	8
Frequency (Hz)	386.20	583.21	1171.50	3927.49	5996.54	6586.33	8826.57	10547.39

3.21 Uniform lattice structure spur gear

The number of nodes on the gear is 112617, and the resulting element is 71081. The number of nodes and elements is more than solid spur gears because the surface of the spur gear with a uniform cubic lattice structure is higher than solid spur gears. Therefore, element values need to be higher to obtain accurate data and values. Table 11 shows the frequency data obtained for cubic uniform lattice structure spur gear.

Table 11: Natural frequency of the uniform lattice structure spur gear

Mode	1	2	3	4	5	6	7	8
Frequency (Hz)	390.88	568.97	1122.06	3685.48	5467.20	6139.55	8244.96	9707.01

3.22 Conformal lattice structure spur gear

The number of nodes on the gear is 44394, and the number of elements is 26440. The nodes and elements are higher than solid spur gears and lattice structure spur gears because the face surface of the conformal lattice structures spur gear consists of more surfaces. Table 12 shows the frequency data obtained for conformal lattice structure spur gear.

Table 12: Natural frequency of the conformal lattice structure spur gear

Mode	1	2	3	4	5	6	7	8
Frequency (Hz)	405.17	559.77	1127.99	3400.12	5146.90	5272.34	7775.10	8962.51

A graph of the frequency versus mode is shown in Figure 12. The conformal spur gear has a lower natural frequency than all the gears for the modal analysis simulation. This study has successfully reduced the vibration of the spur gears after redesigning the spur gears into conformal and uniform cubic-shaped spur gears. All the gears on the graph do not exceed 10000 Hz except the solid spur gear in the eighth mode. Based on the results, spur gears using lattice structures have lower amplitude compared to solid spur gears. This causes the vibrations on solid spur gears to be higher than lattice structure spur gears. The operating frequency of a car is between 15 to 100Hz. While the results obtained for the first modes of the natural frequencies for the conformal and uniform lattice structures are 405 Hz and 390 Hz respectively. Therefore, the natural frequencies for the spur gears with lattice structures can be used in the automotive industry.

Figure 12: Modes against natural frequency

3.3 Results validation and discussion

Based on the static simulations that have been performed, the trend shows that is in good agreement with previous related research published in the literature by Teufelhart et al. [22]. A solid spur gear has the smallest von Mises stress value, followed by a conformally cubic shape and the stress value decreases with increasing strut diameters. Based on conclusions from previous research, the results obtained from this paper are in agreement with conclusions from previous studies that investigated solid and lattice structures in rotating parts. Hussain et al. demonstrated through numerical and experimental studies that lattice structure rotating turbine has higher natural frequencies compared to solid turbines and reduces vibration [23]. Natural frequencies of lattice structure parts increase as its density increases [24].

4.0 CONCLUSION

In this study, spur gear was used as a case study to investigate the integration of lattice structures in spur gears. Nine spur gears were successfully designed and studied, and two types of simulations were conducted, namely static and modal analysis. Cubic lattice structures were designed in uniform and conformal forms with different strut diameters. Based on the results of the study, it was found that conformal cubic pattern spur gear is more suitable for use because the gear has low vibration and stress values compared to other gears. Among all the gears produced, spur gears that use a conformal spur gear pattern also produce lightweight. The outcome of this study contributes to the design of spur gears for the automotive industry to increase performance and weight reduction, in return reducing fuel consumption, and reduce carbon emissions for a greener environment.

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